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Effects of human activities and climate change on the reduction of visibility in Beijing over the past 36 years

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ABSTRACT

Both climate change and intensive human activities are thought to have contributed to the impairment of atmospheric visibility in Beijing. But the detailed processes involved and relative roles of human activities and climate change have not been quantified. Optical extinction of aerosols, the inverse of meteorological visibility is especially sensitive to fine particles < 1.0 μm. These submicron particles are considered more hazardous than larger ones in terms of cardiovascular and respiratory diseases. Here we used the aerosol optical extinction (inverse of visibility) as the indicator of submicron particles pollution to estimate its inter-annual variability from 1980 to 2015. Our results indicated that optical extinction experienced two different periods: a weakly increasing stage (1980–2005) and a rapidly increasing stage (2005–2015). We attributed the variations of optical extinction to the joint effects of human activities and climate change. Over the past 36 years, human activities played a leading role in the increase of optical extinction, with a positive contribution of 0.077 km^{-1}/10 y. While under the effects of climate change, optical extinction firstly decreased by 0.035 km^{-1}/10 y until 2005 and then increased by 0.087 km^{-1}/10 y. Detailed analysis revealed that the abrupt change (around 2005) of optical extinction resulted from the trend reversals of climate change. We found since 2005 the decreasing trend by 0.58 $m \cdot s^{-1}$/10 y in wind speed, the growing trend at 8.69%/10 y in relative humidity and the declining trend by 2.72 hPa/10 y in atmospheric pressure have caused the rapid increase of optical extinction. In brief, the higher load of fine particles < 1.0 μm in Beijing in recent decades could be associated with both human activities and climate change. Particularly after 2005, the adverse climate change aggravated the situation of submicron particles pollution.

1. Introduction

Is there a landmark you can observe clearly on some days and not on others? Well, it is related to atmospheric visibility where you live. Visibility usually refers to the clarity or transparency of the atmosphere, which is defined as horizontal distance at which an observer can just see a black object viewed against the sky background (Koschmieder, 1926). At polluted sites, atmospheric visibility can be impacted by air aerosols through their scattering and absorption of solar radiation. Optical extinction of aerosols, the inverse of atmospheric visibility, is especially sensitive to fine particles < 1.0 μm, because these particles are close to the wavelength of visible solar radiation and are the most effective at reducing atmospheric visibility (Nicole Pauly, 2009; Watson, 2011). The World Health Organizations (WHO) has announced that fine particles are more hazardous to human health than larger ones in cardiovascular and respiratory diseases (Englert, 2004). For this reason, visibility has been a major concern in pollution studies and climatology at local, regional, continental and global scales (Li et al., 2017; Wang et al., 2009; Wang et al., 2012; Zhao et al., 2011). The inverse of optical extinction, meteorological visibility, which has been routinely observed at weather station and globally available from the early 20th century (Vautard et al., 2009; Wang et al., 2012), provides a proxy of the optical concentrations of $PM_{1.0}$. Many studies on meteorological visibility has been used successfully to quantify inter-annual variability of air aerosols over the past decades (Field et al., 2009; Li et al., 2015; Liu et al., 2015; Wang et al., 2009; Wang et al., 2012).

In the past several decades, clear sky visibility has decreased over land globally (Fu et al., 2013; Hua et al., 2015; Sabetghadam et al., 2012; Wang et al., 2009; Wang et al., 2012; Zhao et al., 2011). It has been reported that since 1973 visibility has decreased substantially over

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South and East Asia, South America, Australia and Africa (Wang et al., 2009). The long-term changing assessment of optical extinction of aerosols over the Northern Hemisphere by Wang et al. (2012) also indicated there was a decreasing trend in visibility from 1992 to 2011. China, as the largest developing country, is deemed as one of the most significant emitters of aerosols and their precursor gases (Streets et al., 2003). Visibility impairment has been reported in some mega cities and even some medium and small cities in recent decades (Chang et al., 2009; Liang et al., 2017; Wu et al., 2012).

The studies mentioned above mainly focused on the spatial distribution and changing trend of visibility, which indicated visibility reduction has become a trend across the globe. However, when comparing the mass concentration of aerosols ($PM_{2.5}$ and PM_{10}) with the optical extinction of aerosols over the Northern Hemisphere for a long period, Wang et al. (2012) found the contrasting trends. That is to say though the mass concentration of aerosols has decreased, the optical extinction of aerosols has increased abnormally. This conclusion can be verified by a certain city, such as Beijing (Chang et al., 2009; Kong et al., 2017; Tian et al., 2014; Zhao et al., 2011). Considering the optical extinction of aerosols is especially sensitive to particles < 1.0 μm, we think it could be the increasing fine aerosols (such as $PM_{1.0}$) that led to the increase of optical extinction. A previous study also confirmed that the optical extinction was generally well correlated with the $PM_{1.0}$ mass concentrations (Xu et al., 2016). Therefore, we should pay more attention to those fine particles with sizes of a few microns or less because they are more hazardous than larger ones (Sánchez-Soberón et al., 2015). In view of the close relationships between the optical extinction and fine particles < 1.0 μm, optical extinction can be regarded as the indictor of $PM_{1.0}$ mass concentrations.

Beijing is regarded as the political, economic and cultural center of China, but the city is facing the challenge of the deterioration of visibility due to the growing intensity of human activities (Chang et al., 2009; Zhao et al., 2011). To maintain the good impression of the city in people's mind, the government has adopted a series of control measures, including adjusting industrial structure, using clean energy, limiting the number of private cars and establishing the joint prevention and control work with neighboring provinces (Hu et al., 2013; Liang et al., 2018; Pope et al., 2017; Zhang et al., 2010). However, the effect was not obvious. The most mentioned event is the record that in January 2013, the atmospheric visibility of Beijing was extremely low and the $PM_{2.5}$ concentrations reached up to 996 μg/m^3 (Li et al., 2017; Uno et al., 2014; Zheng et al., 2015). So it appears that meteorological conditions may be another critical factor that contributes to such serious pollution, besides the impact of human activities. Hence, both anthropogenic and meteorological factors are responsible for the impairment of visibility in Beijing. However, it is unclear how much the visibility reduction is caused by human activities and how much is caused by climate change.

In summary, optical extinction of aerosols is well associated with the mass concentrations of fine particles < 1.0 μm. Over the past decades, the increase of submicron particles mass concentrations in Beijing has contributed to the visibility reduction. We should attribute the pollution of submicron particles to the combined effects of human activities and climate change, rather than single factor. However, we cannot directly analyze the submicron particles pollution, because the long-term observational data for $PM_{1.0}$ is unavailable. In this study, we considered the optical extinction measurement as the indicator of submicron particles to estimate its inter-annual variability and driving factors from 1980 to 2015. While quantifying the relative roles of human activities and climate change, we used the linear regression model to separate their individual effects on optical extinction. The aim of this paper is to figure out how human activities and climate change influence the changing trend of submicron particles pollution through the optical extinction data.

2. Methodology and materials

2.1. Study region

Beijing (39°54′N, 116°25′E), the capital of the People's Republic of China, is located in the North China Plain. The city is influenced by a sub-humid warm temperate continental monsoon climate, and experiences a hot and humid summer, and a cold and dry winter. In recent decades, Beijing has witnessed tremendous changes due to the rapid economic development and urban sprawl under the reform and opening-up policy (W. Chen et al., 2016; Wang et al., 2007; Y. J. Zhang et al., 2015). Nevertheless, the achievements on economic development was at the cost of negative environmental consequences. Chang et al. (2009) illustrated a downward trend of visibility from 1973 to 2007, using the visibility data in Beijing from National Climate Data Center. The government had adopted a series of measures to reduce the emissions of air pollutants and improve air quality (Hu et al., 2013; Zhang et al., 2010), but the effect was unsatisfactory. In recent years, Beijing has experienced the extremely severe and persistent haze pollution in autumn and winter (Wang et al., 2016; Yang et al., 2015). These results indicated visibility reduction in Beijing is governed by anthropogenic and meteorological factors.

2.2. Data sources and preparation

Daily atmospheric visibility and meteorological data, including wind speed (WS), temperature (TEM), air pressure (PRES), and indicators for the occurrence during the day of fog, rain, snow and tornado were obtained from Global Summary of the Day from the National Climate Data Center of the U.S. Department of Commerce (available at: https://www.ncdc.noaa.gov/). Visibility in the daytime is measured using a barely distinguished black object silhouetted against the horizontal skyline. Additionally, relative humidity (RH) data were obtained from the China National Meteorological Information Center (available at: http://www.cma.gov.cn/). Both visibility and other meteorological data have been recorded in Beijing airport from 1980 to 2015. Daily data were obtained by mathematically averaging a minimum of four synoptic observations per day. Our results were based on annual averaged data, which were calculated from the daily meteorological observations.

To investigate the impact of climate change on atmospheric visibility, the observed days under the extreme meteorological conditions, such as rain and fog resulted in very low visibility, were eliminated (Chang et al., 2009; Gao et al., 2011). Furthermore, visibility data with relative humidity above 90% were also screened out because high humid environment contributed to hygroscopic particle increasing by five or more times in the scattering cross section (Malm and Day, 2001).

Human activities data including the gross domestic product (GDP), vehicle holdings (VH), total population (TP) and energy consumption (EC) were collected from Beijing Municipal Bureau of Statistics (available at: http://www.bjstats.gov.cn/). Further correlation with aerosol optical extinction would be analyzed to understand the influence of human activities in Beijing over the past 36 year of 1980–2015.

2.3. Statistical analysis

The presence of aerosols and hydrometeors in atmosphere is able to cause visibility impairment. Eliminating the influence of hydrometeors on visibility allows an estimation of the near-surface optical extinction coefficient of aerosols (Husar et al., 2000). In this paper, we used relative humidity to correct optical extinction for obtaining dry extinction coefficients, which can better reflect the concentration levels of fine aerosols (those < 1.0 μm) (Deng et al., 2012). The *RH* corrected extinction coefficient, which is called dry extinction coefficient, was estimated by the following formula (Eq. (1)) (Husar and Holloway, 1984):

$$IV = \begin{cases} \frac{IV^w}{0.85}\,(RH \le 30\%) \\ \frac{IV^w}{(RH-30\%)*0.5+0.85}\,(30\% < RH \le 40\%) \\ \frac{IV^w}{(RH-40\%)*0.5+0.90}\,(40\% < RH \le 50\%) \\ \frac{IV^w}{(RH-50\%)*0.5+0.95}\,(50\% < RH \le 60\%) \\ \frac{IV^w}{(RH-60\%)*0.5+1.00}\,(60\% < RH \le 70\%) \\ \frac{IV^w}{(RH-70\%)*0.3+1.05}\,(70\% < RH \le 75\%) \\ \frac{IV^w}{(RH-75\%)*0.4+1.20}\,(75\% < RH \le 80\%) \\ \frac{IV^w}{(RH-80\%)*0.5+1.40}\,(80\% < RH \le 85\%) \\ \frac{IV^w}{(RH-85\%)*0.29+1.65}\,(85\% < RH \le 90\%) \end{cases} \tag{1}$$

where the IV is the "dry extinction coefficient", RH is the relative humidity, and IV^w is the "wet extinction coefficient" (uncorrected extinction coefficient) which is calculated via the Koschmieder relationship $IV^w = {}^{3.912}/_V$ (Koschmieder, 1926). Here, V represents the visibility with unit of km.

Here, we used IV as the indicator of fine particles < 1.0 μm. Generally, the IV value increases with the increase of $PM_{1.0}$ mass concentrations, and decreases with the reduction of $PM_{1.0}$ mass concentrations.

In this study, the linear regression model was used to investigate the long-term variations of optical extinction under the impacts of human activities and climate change in Beijing from 1980 to 2015. In the model, anthropogenic and climatic factors were the input variables. A summary of these variables can be found in Table 1. The regression formula is written as follows (Eq. (2)):

$$Y_{IV} = X_{CC} + X_{HA} + C \tag{2}$$

where Y_{IV} is the total optical extinction coefficients, X_{HA} denotes the optical extinction induced by human activities, X_{CC} denotes the optical extinction induced by climate change and C denotes the constant intercept.

To avoid that relatively small changes in driving factors have a too large influence on the optical extinction, independent variables and dependent variable in the regression model were first standardized (Eq. (3)):

$$X_{ST}(i) = \frac{X(i) - \mu(X)}{\sigma(X)} \tag{3}$$

where $X_{ST}(i)$ is the standardized value, i is the number of years from 1980 to 2015, $X(i)$ is the original value in the i year, $\mu(X)$ is the mean value of time series, $\sigma(X)$ is the standard deviation of time series.

From the regression model above, we can obtain the annual optical extinction respectively induced by human activities and climate change. Then, we adopted the slope of the linear regression to analyze the trend in optical extinction from 1980 to 2015. The slope is calculated as follows (Eq. (4)):

$$Slope\,(X) = \frac{n \times \sum_{j=1}^{n} [j \times X(j)] - \left(\sum_{j=1}^{n} j\right)\left[\sum_{j=1}^{n} X(j)\right]}{n \times \sum_{j=1}^{n} j^2 - \left(\sum_{j=1}^{n} j\right)^2} \tag{4}$$

where $Slope$ (X) indicates the variation trend of optical extinction, j is the number of years from 1 to 36, n is the year range, and $X(j)$ is the annual average optical extinction coefficients in the jth year. When $Slope\,(X) > 0$, the optical extinction has an increasing trend, and when $Slope\,(X) < 0$, the optical extinction shows a decreasing trend.

In the study, we mainly used the regression formula (Eq. (2)) to separate the effects of human activities and climate change. In the regression model, all anthropogenic and climatic factors were added into the input variables. Then, according to anthropogenic factors in the model, we can calculate the effects of human activities; while according to the climatic factors in the model, we were able to acquire the impacts of climate change.

Table 1
The description of variables of anthropogenic and climatic factors from 1980 to 2015.

	Parameter	Units	Range	Mean	Standard deviation (SD)
Human activities	GDP	$\times 10^8$ yuan	139.1–23014.6	5546.01	6898.3
	VH	$\times 10^4$	8.09–561.90	179.13	191.1
	TP	$\times 10^4$	904.3–2170.5	1380.32	399.9
	EC	TSC[a]	1903–6853	4068.14	1641.8
Climate change	WS	m/s	2.07–3.29	2.73	0.3
	RH	%	40.56–54.32	46.99	3.3
	TEM	°C	9.67–13.24	11.16	0.8
	PRES	hPa	1011.6–1015.4	1013.42	1.0

[a] TSC means tons of the standard coal.

3. Results and discussion

3.1. Temporal variations in aerosol optical properties

The optical extinction of aerosol is an important parameter that can reflect the actual mass concentrations level of fine particles < 1.0 μm in atmosphere. High optical extinction indicates the high submicron particles pollution. Here, the annually, seasonally and monthly averaged variations in optical extinction were analyzed, as shown in Fig. 1a, b and c.

Beijing witnessed a noticeably 36-year variation in optical extinction (Fig. 1a). It could be divided into two distinguishable periods, 1980–2005 and 2005–2015, respectively. During the first period, optical extinction showed a weakly increasing trend, with a growth rate of 0.006 km^{-1}/10 y. However, during the second period, there was a rapid increase in optical extinction, with a growth rate of 0.298 km^{-1}/10 y, which was significantly more than that of the first period. The rapid increase of optical extinction in Beijing after 2005 could be related to the increasing intensity of the human activities as well as adverse meteorological factors. The following sections would quantify the relative roles of anthropogenic and climatic factors.

Fig. 1b shows the seasonal optical extinction coefficients in Beijing. Seasonally, the highest optical extinction levels occurred during the winter while the lowest during the summer. Fossil fuel combustion and biomass burning and unfavorable meteorological conditions in winter are likely to be important for seasonal maximum air pollutant concentrations, leading to an enhancement of light scattering that affects the impairment of visibility. Summer was the season with the lowest optical extinction due to the lower energy consumption.

Interestingly, changes in monthly averaged optical extinction conformed to a W-shaped characteristic (Fig. 1c). There were three local maximum values respectively in January, July and December, accompanied by two local minimum values respectively in May and September. July is the hottest month in Beijing. Accordingly, it takes more energy supply for air conditioning and refrigeration, resulting in more air pollutant emission and the increase of optical extinction. However, optical extinction in July only increases a little bit, significantly less than that in the winter months. This is mainly due to the favorable meteorological conditions for pollution dispersion in summer months (generally, high atmospheric boundary layer and more precipitation) (H. Zhang et al., 2015).

From 1980 to 2015, optical extinction maintained an increasing trend, especially in the latter stage of 2005–2015. Such severe situation indicates the submicron particles are becoming worse due to the lack of awareness of environmental protection in the process of urban sprawl and socioeconomic development. Seasonal and monthly optical extinction reflects the characteristics of inner-annual variations. Owing to

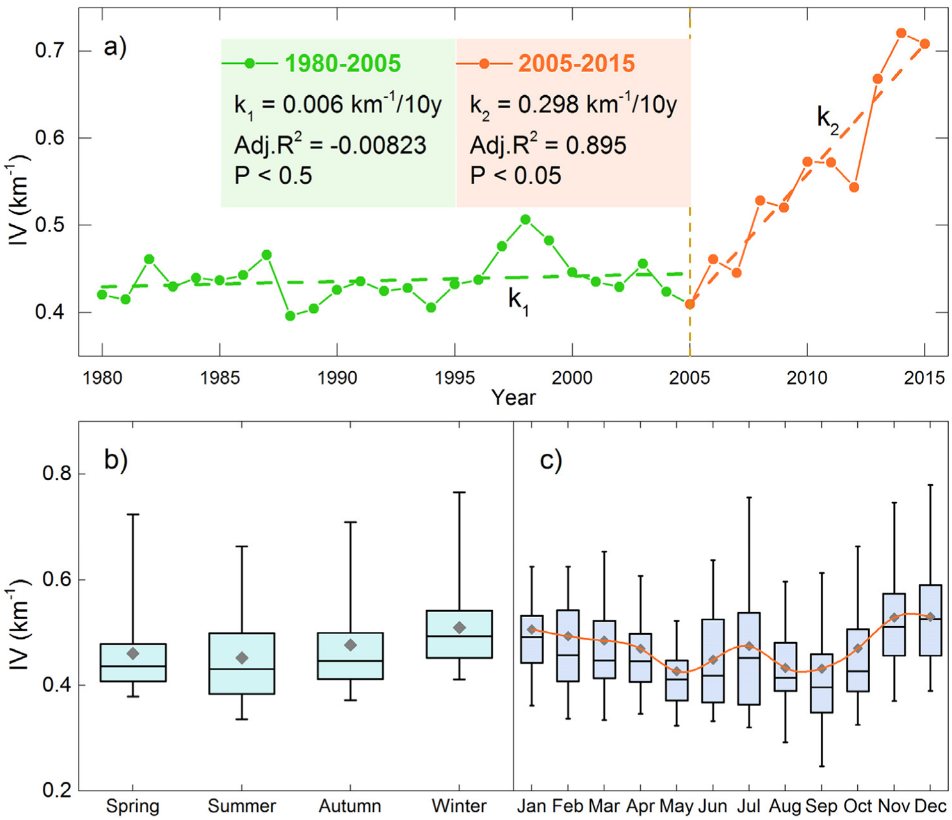

Fig. 1. Statistical variations in aerosol optical extinction (inverse of visibility), annually (a), seasonally (b) and monthly (c) during the period of 1980–2015 for Beijing. In the box-and-whisker plots, the whisker top, whisker bottom, box top and box bottom represent the 95th, 5th, 75th, and 25th percentiles, respectively. The line across the box is the median of the distribution, and the diamond symbol represents the mean value.

the important influences of air quality on people's daily life, the causes of the increasing optical extinction need to be understood and studied in the following sections. Here, we focused on the estimation of relative effects of human activities and climate change on the long-term variation characteristics of optical extinction.

3.2. Effects of human activities

Quantification of human activities factors driving air quality changes is crucial (Wang et al., 2017). Industry, energy consumption, vehicles and other socioeconomic factors are significantly associated with atmospheric aerosols (Fang et al., 2016; Wang et al., 2017). However, current researches are focused on regional and relatively short-term scale. The long-term effects of human activities on the air quality changes are seldom reported.

Fig. 2a shows the variations in anthropogenic factors including the gross domestic product (GDP), vehicle holdings (VH), total population (TP) and energy consumption (EC) over the past 36 years of 1980–2015 in Beijing. Since the policy of reform and opening up to the outside world, Beijing, as the economic and political center, has kept fast development of urbanization. Human activities including GDP, VH, TP and EC increased sharply and reached to the maximum values at the end of 2015. At the same time, tremendous pollutant emission caused serious atmospheric pollution problems. The policy however was compelled to change due to the Olympic Games for better air quality (Wang et al., 2014). Some pollution control strategy has been taken, such as adjusting industrial structure, using clean energy, limiting the number of private cars and establishing the joint prevention and control work with neighboring provinces (Hu et al., 2013; Zhang et al., 2010).

The impact of human activities on aerosol optical extinction can be analyzed by modeling the relationship between anthropogenic factors and optical extinction (Fig. 2b). Here, we calculated the averaged normalized value of four anthropogenic factors and qualitatively estimated their effects on optical extinction. We found between 1980 and 2004 optical extinction impacted by human activities had little change. This was mainly due to the limited intensity of human activities during the period, which could be seen from Fig. 2a. Moreover, there could be some other factors influencing the optical extinction such as climate change. However, after 2005, there was an apparently increasing trend (slope = 0.427, R^2 = 0.864), which suggested optical extinction under the impact of human activities increased rapidly. Despite all this, it was too early to say human activities caused the rapid increase of optical extinction since 2005. It was worth noting that climatic factors also influenced the variations in optical extinction. In the following section, we would like to discuss the impact of climate change.

3.3. Impact of climate change

Adverse meteorological conditions can greatly increase the risk of haze pollution and cause low visibility (Zhang et al., 2010). To reveal what meteorological conditions could result in air pollution and avoid the interference effect of anthropogenic factors, all days each year were grouped into two categories, heating seasons and non-heating seasons, respectively. During the heating seasons (non-heating seasons), we assume that the intensity of human activities almost has no change, so the effects of climatic factors on optical extinction can be effectively analyzed. The variations of climatic factors under the conditions of the best 20% and worst 20% visibility are depicted in Figs. 3 and 4. Then the trends of four climatic factors including annual averaged wind speed, relative humidity, temperature and atmospheric pressure are shown in Fig. 5.

Both in heating seasons and non-heating seasons, we found the similar characteristics of climatic factors. Among four climatic factors, wind speed and relative humidity had obvious differences between the best 20% and worst 20% visibility. In terms of wind speed, the higher the wind speed was, the better the visibility was (Figs. 3a and 4a). It is easy to see that high wind speed can contribute to the dispersion of submicron particles. For the last three years (2013–2015), the wind

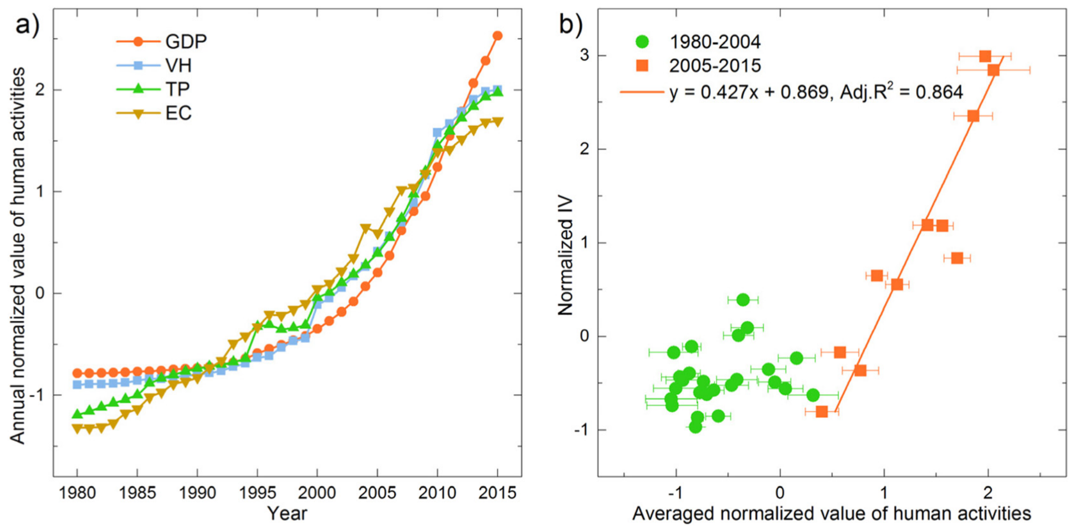

Fig. 2. (a) Annual normalized values of human activities including GDP, VH, TP and EC during the period of 1980–2015 in Beijing. (b) Curve plots of averaged normalized value of human activities as a function of annual normalized value of aerosol optical extinction (inverse of visibility).

speed in the best 20% visibility was significantly lower than before, which could facilitate the increase of optical extinction. Relative humidity in the best 20% visibility was much lower than that in the worst 20% visibility (Figs. 3b and 4b). This is due to that fuel burning from the local and regional transport can produce a lot of hygroscopic species, and high relative humidity could facilitate the bigger scattering cross section of hygroscopic particles (Hu et al., 2015; Hu et al., 2008). For the last three years (2013–2015), we observed higher relative humidity in the best 20% visibility, which also suggested the increasing tendency of optical extinction. Nevertheless, the differences of temperature and atmospheric pressure between high and low visibility were weaker. But it remained to be seen that temperature in the best 20% visibility was slightly lower than that in the worst 20% visibility (Figs. 3c and 4c), which was different from the common sense that high temperature means good air quality, especially in summer. Here we consider it is related to the photochemical reaction, and high temperature results in the increase of photochemical reaction and produces more aerosol pollution. For atmospheric pressure (Figs. 3d and 4d), atmospheric pressure in the best 20% visibility was slightly higher than that in the worst 20% visibility. This is because when the atmosphere is controlled by high atmospheric pressure, air masses near the ground spread to the surrounding air because of the horizontal divergence.

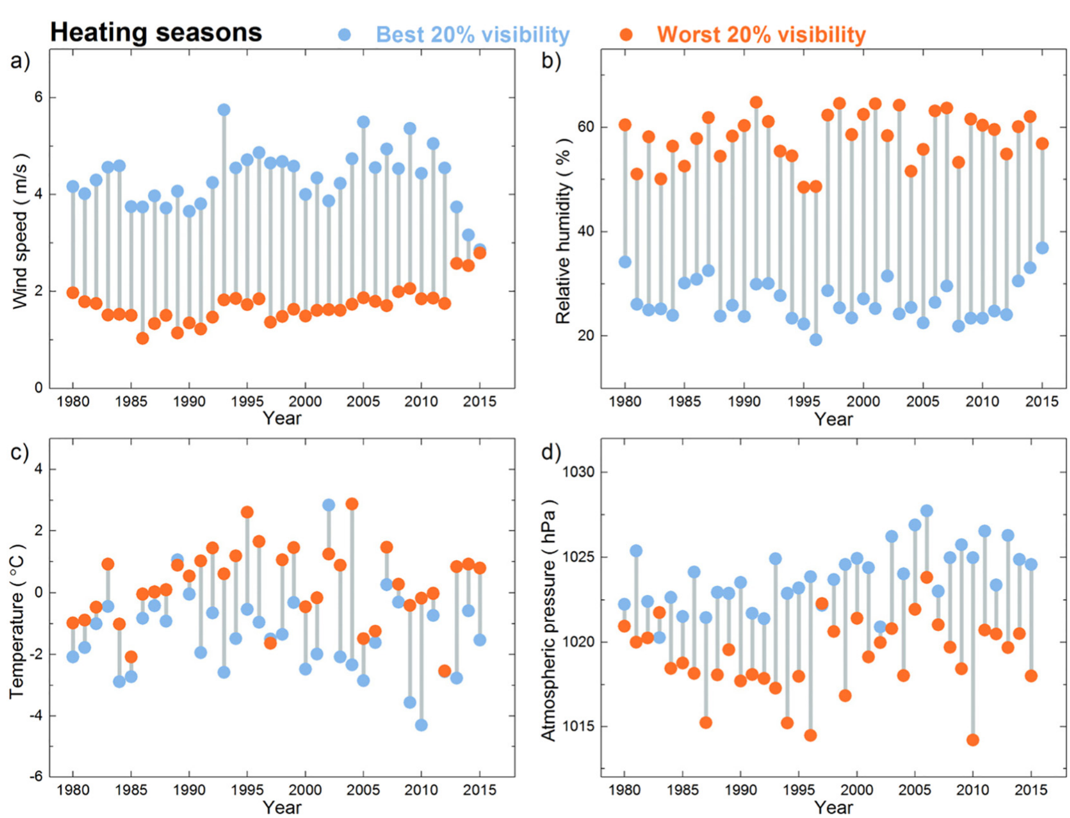

Fig. 3. Meteorological conditions including wind speed, relative humidity, temperature and atmospheric pressure respectively under the best 20% and worst 20% visibility in heating seasons in Beijing.

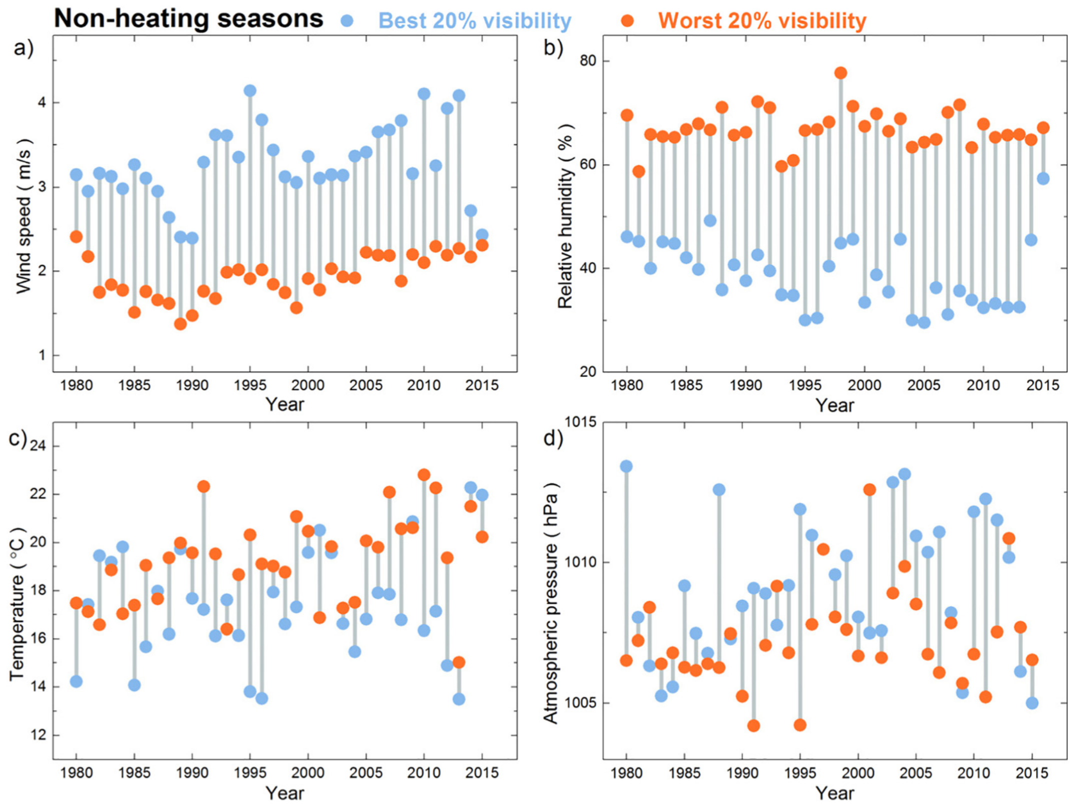

Fig. 4. Meteorological conditions including wind speed, relative humidity, temperature and atmospheric pressure respectively under the best 20% and worst 20% visibility in non-heating seasons in Beijing.

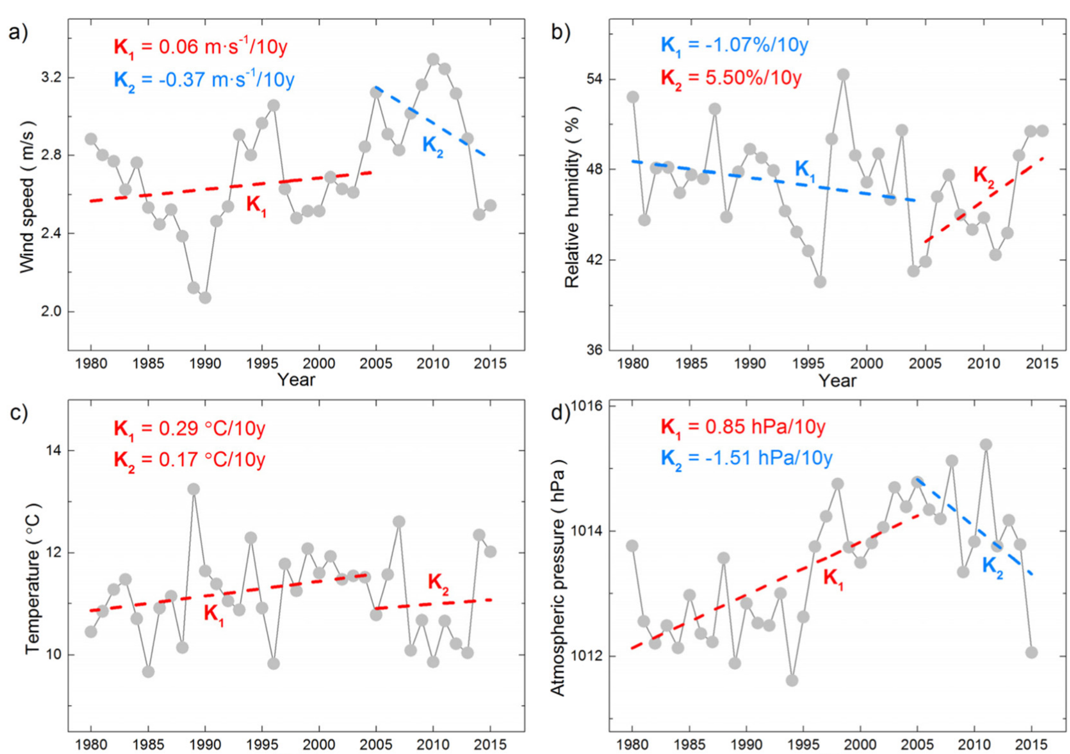

Fig. 5. Trends of annual averaged wind speed (a), relative humidity (b), temperature (c) and atmospheric pressure (d) for the period of 1980 to 2015 in Beijing. The red dotted line represents the positive trend and the blue dotted line represents the negative trend. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Consequently, the high concentrations of air pollutants within air masses could be transported to other regions, so the optical extinction decreased.

In the study, climatic factors had significantly annual variation characteristics (Fig. 5). We found that four climatic factors including wind speed, relative humidity, temperature and atmospheric pressure fluctuated greatly over the past 36 years. In the relatively short temporal scale, the increasing or decreasing trends were observed, which could have a significant influence on the optical extinction. According to a threshold point around 2005 after which optical extinction had a large change, we analyzed the variation trends of climatic factors during the two different periods of 1980–2005 and 2005–2015, respectively. For example, before the year of 2005, wind speed had a weakly increase ($0.06\ m{\cdot}s^{-1}/10\ y$), after which there was a rapid decrease ($-0.37\ m{\cdot}s^{-1}/10\ y$). For the atmospheric pressure, there was a similar trend just like wind speed, increasing (0.85 hPa/10 y) in the first period and decreasing (−1.51 hPa/10 y) in the second period. However, for the relative humidity, there was a weakly decreasing trend (−1.07%/10 y) before 2005 and a rapidly increasing trend (5.50%/10 y) after 2005. By the comparisons of the meteorological characteristics between haze days and clean days, we had known that the lower wind speed, higher relative humidity and lower atmospheric pressure could cause the deterioration of visibility. Hence, the variation trends of climate change after the year of 2005 could result in the abrupt change of optical extinction. However, in terms of temperature, the annual averaged trend had been basically flat over the past 36 years, and there could be little effect on optical extinction.

3.4. Relative roles of human activities and climate change

Based on the above analysis on anthropogenic and climatic factors, here we quantified the relative roles of human activities and climate change on optical extinction. Because four different anthropogenic factors had strong collinearity, the averaged values of human activities were therefore calculated as the input variable-“HA”. So one averaged normalized anthropogenic factor (HA) and four normalized climatic factors (WS, RH, TEM and PRES) were selected into the regression model. Fig. 6a shows the variations of normalized value of optical extinction under the impacts of human activities and climate change, respectively. Based on the normalization equation, the normalized value of optical extinction can be converted to the actual value. The finally nice performance of regression model is shown in Fig. 6b (Adj. $R^2 = 0.87$, $P < 0.05$, RMSE = 0.029). Using the year of 1980 as baseline year, Fig. 7 depicts the variation characteristics of optical extinction induced by human activities and climate change, respectively.

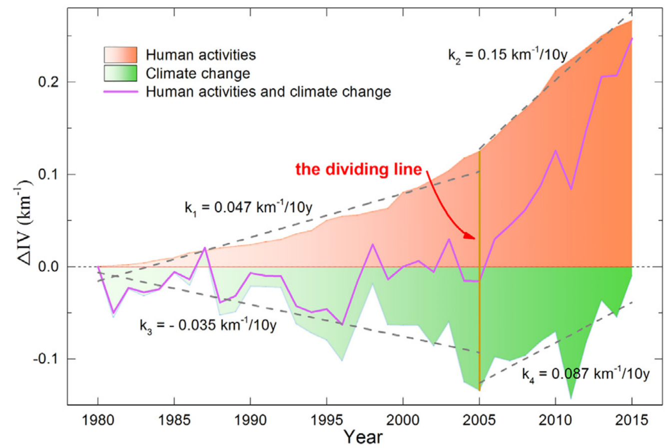

Fig. 7. Alteration of optical extinction (inverse of visibility) respectively induced by human activities and climate change while specifying 1980 as baseline year.

Under the influence of human activities, optical extinction increased rapidly with the intensifying human activities. During the two periods of 1980–2005 and 2005–2015, the optical extinction induced by human activities had a powerfully increasing trend, with a growth rate of $0.047\ km^{-1}/10\ y$ and $0.15\ km^{-1}/10\ y$, respectively. Overall, between 1980 and 2015, the trend of optical extinction affected by human activities was $0.077\ km^{-1}/10\ y$ (Table 2).

However, under the impact of climate change, it could be divided into two different periods: 1980–2005 and 2005–2015, respectively. During the first period of 1980–2005, optical extinction under the effect of climate change showed a generally weakly decreasing trend, with a descent rate of $-0.035\ km^{-1}/10\ y$. The result indicated that climate change facilitated the improvement of air visibility during the period. During the second period of 2005–2015, however, climate change significantly increased the optical extinction, with a growth rate of $0.087\ km^{-1}/10\ y$. The result suggested there were more adverse meteorological conditions that increased the optical extinction during the period. Seen from Fig. 5, it was the sudden reversals of trends of wind speed, relative humidity and atmospheric pressure that resulted in visibility impairment after 2005. We found there were decreasing

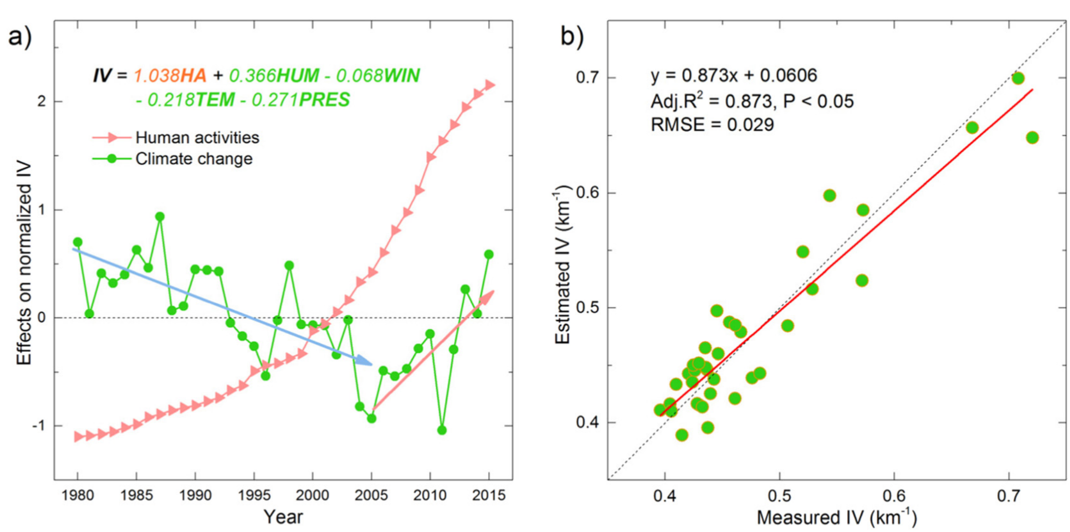

Fig. 6. (a) Estimation on normalized optical extinction (inverse of visibility) respectively under the impacts of human activities and climate change during the period of 1980–2015. (b) Estimated versus measured annual optical extinction (inverse of visibility). The dashed line corresponds to perfect fit (y = x), while the solid line to the least-square fit.

Table 2
The relative roles of human activities and climate change on the optical extinction over the past 36 year (1980–2015).

Periods	The impact of human activities/(km^{-1}/10y)	The impact of climate change/ (km^{-1}/10y)	The overall impact/(km^{-1}/10y)
1980–2005	0.047	−0.035	0.012
2005–2015	0.15	0.087	0.237
1980–2015	0.077	−0.021	0.056

trends for wind speed and atmospheric pressure and increasing trend for relative humidity after 2005. Between 2005 and 2015, the mean wind speed decreased by 0.58 m/s, relative humidity increased by 8.69% and atmospheric pressure decreased by 2.72 hPa. For temperature, it had a large fluctuation range and the trend was not clear. As a whole, over the past 36 year, climate change decreased the optical extinction, with a descent rate of $-0.021\ km^{-1}/10\ y$ (Table 2).

Through the above analysis, it could be concluded that variations in optical extinction affected by climate change were obviously different from those affected by human activities. The alteration of optical extinction based on climate change fluctuated in a relatively small scope. Moreover, the alteration of optical extinction impacted by climate change was generally below zero specifying 1980 as a baseline year, which indicated the effects of climate change could offset part of effects of human activities to some extent. In the current study, the year of 2005 was a threshold point after which optical extinction experienced a rapid increase. In addition, we also found a mutation in climate change around 2005, a decreasing trend before 2005 and an increasing trend after 2005. The results indicated that the rapid alteration of optical extinction around 2005 resulted from climate change, rather than human activities. Nevertheless, the influence of human activities played a leading role and had determined the trend of optical extinction.

Though many scholars have reported that the severe winter haze is driven by stable synoptic meteorological conditions (Y. Chen et al., 2016; Zheng et al., 2015), their studies just focus on relatively short temporal scale, not long-term temporal scale. During the long-term variations of optical extinction, our studies found two significantly different periods. Before 2005 there existed an antagonistic relationship between climate change and human activities. That is to say the effect of climatic factors on optical extinction could offset the impact of human activities to some extent. However, after 2005, both climate change and human activities had positive impacts on the increase of optical extinction. It is worth noting that in this paper we paid more attention to the fluctuation and uncertainty characteristics of climatic factors, so we didn't use the complex nonlinear model to estimate their effects on optical extinction. Even so, our model remained to give the nice model fit. In addition, considering that the effects of climate change on optical extinction existed complex fluctuation and uncertainty characteristics, we should consider the long-term impact of climate change when establishing related air environmental policies.

4. Limitations

In this study, we investigated the relative roles of climate change and human activities on optical extinction in Beijing. It should be noted that the selected variables of climate change only included four typical factors, i.e., wind speed, relative humidity, temperature and atmospheric pressure. We ignored the impacts of wind direction, sunshine hours and other meteorological elements. In terms of the intensity human activities, we selected four critical factors including GDP, vehicle holdings, total population and energy consumption. As for emission inventories data, because the data collection was only held for recent few years, which didn't meet the requirement of long time series, here we gave up the use of emission inventories. In addition, the regional transport may also have influence on the air quality in Beijing. But the regional transport is connected with wind speed and wind direction. A previous source apportionment in Beijing indicated the contribution of long-range transport was only 12.5% around the heating period of 2014, and even 5.3% around the before-heating period (Yang et al., 2016). Hence, regional transport has little impact on air quality in Beijing. In this paper, we paid more attention to the fluctuation and uncertainty characteristics of climatic factors in the inter-annual variation. So we didn't use the complex nonlinear model to estimate their effects on optical extinction. Even so, our linear model remained to give the same nice model fit.

5. Summary and conclusions

This study provided insights about how human activities and climate change influenced the changing trend of submicron particles pollution based on the optical extinction data in Beijing over the past 36 years. The results indicated that there existed a threshold point around the year of 2005 on the optical extinction curves. The optical extinction maintained a weakly increasing trend until 2005 after which the trend began to increase rapidly. We then quantified the relative roles of human activities and climate change on the optical extinction.

It concluded that human activities played a leading role on the increasing optical extinction. Between 1980 and 2015, the optical extinction induced by human activities had a generally powerfully increasing trend, with a growth rate of $0.077\ km^{-1}/10\ y$. In terms of climate change, however, since 1980 the effects on optical extinction resulted from climate change had a decreasing trend, with a descent rate of $-0.021\ km^{-1}/10\ y$. Further analysis found that optical extinction impacted by climate change actually experienced two periods: an initially decreasing stage (1980–2005) and then a rapidly increasing stage (2005–2015), respectively. Hence, we could concluded that the threshold point (around 2005) of optical extinction during the period of 1980–2015 was induced by climate change, not by human activities. Concretely, we found there were decreasing trends for wind speed and atmospheric pressure and increasing trend for relative humidity since 2005. These results suggested that we should consider the fluctuation characteristics of climate change for a long-term periods while establishing related environmental policies.

Despite all this, we should note that in recent decades some environmental control measures had been taken to mitigate the air pollution. Though air mass concentrations have been improved, it is only effective for those larger particles such as $PM_{2.5}$ and PM_{10}. Visibility reduction in Beijing suggests the increasing trend of the fine particles $< 1.0\ \mu m$ in atmosphere. Our studies estimated the relative roles of human activities and climate change on optical extinction for a long period. In the future studies, more attentions should be paid to these submicron particles because they are more harmful than larger ones.

Conflict of interest statements

The authors declare on competing interests related to this project.

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